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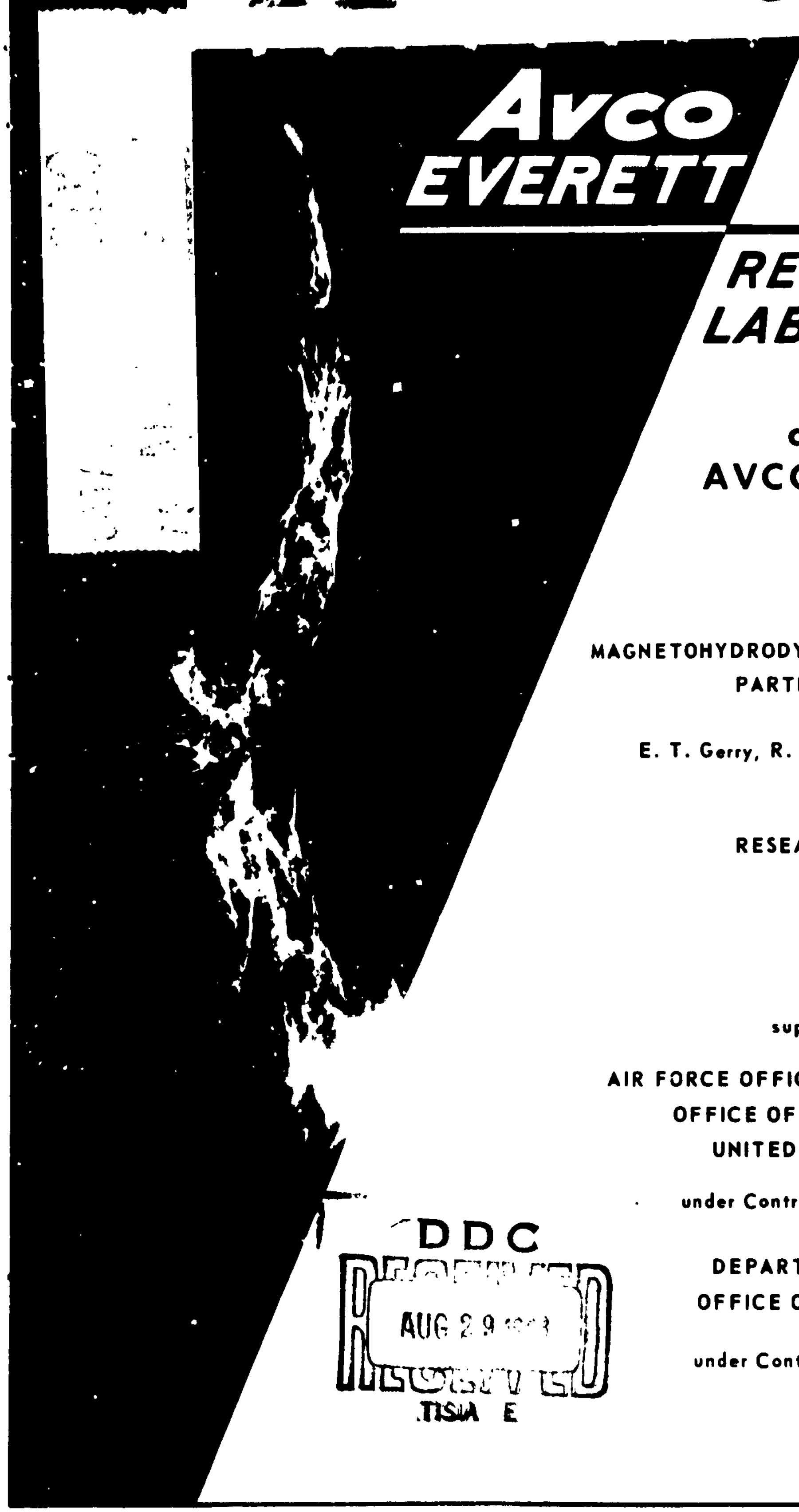

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MAGNETOHYDRODYNAMIC SHOCK STRUCTURE IN A PARTIALLY IONIZED GAS

E. T. Gerry, R. M. Patrick and H. E. Petschek

RESEARCH REPORT 153
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ABSTRACT

A study has been made of strong MHD shock waves in partially ionized hydrogen. Dissipation due to slip between the ions and neutrals with the effects of viscosity and heat conductivity have been included. Charge exchange processes control viscosity and ion slip. For Alfven Mach numbers below 2.5, the dominant mechanism is ion slip; for larger Mach numbers, the viscosity is important. The measured light intensity rise time and the electron temperature immediately behind the shock agree with theory. Behind the shock, measured electron temperatures are low. Electron temperatures are obtained by measuring the plasma soft x-radiation using thin carbon foils as filters.

1. Introduction

The magnetic annular shock tube (MAST) has been suggested previously[1, 2] as a useful tool for producing high temperature (≃ 100 ev) plasma samples for study. Earlier work[3, 4] has shown that the device does operate as a shock tube in that there is a region behind the shock in which the density and magnetic field are uniform and satisfy the conservation conditions across the shock. In addition, the MAST has been used to study the structure of high velocity shocks, (≈ 40 cm/μs). The present paper discusses further work on both of these problems.

The observed shock thickness[5] has previously been found to be in agreement with a theory for the structure of a shock wave in a collision-free fully ionized plasma. The fact that the shock wave was proceeding into un-ionized or at best partially ionized hydrogen was assumed to be unimportant because the energy dissipated in the shock was many times (≃ 30) the ionization energy of hydrogen. This assumption is probably invalid since several dissipative mechanisms can be found in a partially ionized gas which are capable of dissipating appreciably more than the ionization energy. In Section 2 these mechanisms are discussed and compared with the experimental results. Although the explanation of the experimental results is not complete, the general scale of the thicknesses is of the right order of magnitude. This suggests that the observed shock structure is probably related to the gas being partially ionized and should not be compared to collision-free shock theories.

Section 3 discusses attempts to determine the energy distribution in the gas behind the shock wave. A soft (≃ 200 ev) x-ray detector has been developed. Assuming a Maxwell electron distribution, the apparent electron temperature never exceeds 25 ev. In the times available, collisional heating by the ions should give temperatures two or three times higher. This discrepancy is at present unresolved. The possible explanation that the thermal energy is lost to the walls is in disagreement with measurements of wall heat transfer.[3, 5]

2. Shock Thickness

Discussion

In the discussion of the structure of strong magnetohydrodynamic shock waves in a partially ionized gas, the relevant collision cross sections to be considered are those whose magnitude does not decrease rapidly at

high energy. For most simple gases, the ion-ion and neutral-neutral cross sections are inversely proportional to the square of the energy for large relative energy. Those which remain large at high energy are the neutral-ion charge-exchange and the electron-neutral ionization cross sections. Dissipation mechanisms can be constructed based on both of these processes occurring in the presence of a magnetic field.

We consider strong shock waves propagating into a partially ionized gas containing a magnetic field in the plane of the shock front. If the ratio of ion mean free path to gyro-radius is large, then the ion gas will essentially be tied to the magnetic field and within the shock a relative velocity will exist between the ion and neutral gases. Ionization or charge-exchange taking place where this difference of velocities exists will result in a friction force between the two gases.

The heavy particle distribution produced by such a mechanism is non-Maxwellian. It is essentially a two-dimensional Maxwellian distribution in the plane normal to the magnetic field cut off at the velocity $v_{max} = U_1 - U_2$, where U_1 and U_2 are the gas velocities ahead and behind the shock in shock fixed coordinates. If the charge-exchange and ionization cross sections are large compared to any actual momentum collision cross section, then complete Maxwellization of the ions will occur considerably behind the shock. A ratio of specific heats, γ, equal to two is appropriate to this intermediate distribution and will be used in most of the subsequent calculations.

If the ratio of U_1, to the Alfven speed ahead of the shock $(B_1^2/4\pi\rho_1)^{\frac{1}{2}}$ is two, which we will call the Alfven Mach number, M_A, the Rankine-Hugoniot relations give $U_2 = \frac{1}{2} U_1$ for $\gamma = 2$. In this case, the particles having v_{max} in the final velocity distribution can just stand still in the

stream, none can propagate upstream. For $M_A \leq 2$ then viscosity effects can play no role in a shock structure based on charge-exchange or ionization. For $M_A > 2$, some particles in the distribution will be able to travel upstream and some effects of viscosity would be expected. For large M_A, these viscosity effects will become dominant.

In the case where viscosity can play no role ($M_A \leq 2$) there is an upper limit on the initial degree of ionization, if the mechanism of the shock is to remain charge-exchange or ionization. This limit is the result of the fact that there must be some mechanism by which information may be transmitted ahead of the shock. If no particles can go forward, then a wave propagation mechanism is required to carry information to the front of the shock. Since the ion and neutral gases are relatively decoupled, it is possible to propagate a transverse magnetohydrodynamic wave[5] across the field lines with a velocity equal to $(B^2/4\pi\rho_I)^{\frac{1}{2}}$ where ρ_I is the ion density. This wave will propagate ahead of the shock as long as the initial degree of ionization is less than $(1/M_A^2)$. Thus, for $M_A \leq 2$, this requirement sets a limit on the allowed initial degree of ionization. For $M_A > 2$, particles can propagate ahead and the condition is relaxed to a degree depending on M_A.

We will divide the further discussion into two parts, those cases where the effects of viscosity may be neglected, and those cases where viscosity must be included.

<u>Low Alfven Mach Number Case</u>

When viscous effects are neglected, conservation equations for total mass, momentum and energy, summed over all the species, (ions, neutrals and electrons) hold throughout the shock region.

$$\underline{\text{Mass}} \qquad \rho_N U_N + \rho_i U_i = \rho_1 U_1$$

$$\underline{\text{Momentum}} \qquad p_N + p_i + p_e + \rho_N U_N{}^2 + \rho_1 U_1{}^2 + B^2/8\pi = \rho_1 U_1{}^2 + B_1^2/8\pi$$

$$\underline{\text{Energy}} \qquad \tfrac{1}{2}\rho_N U_N{}^3 + \tfrac{1}{2}\rho_i U_i{}^3 + \frac{C_p}{R} p_i U_i + \frac{C_p}{R} p_N U_N + \frac{C_p}{R} p_e U_i$$

$$+ \rho_i E_i U_i + U_1 B^2/4\pi = \tfrac{1}{2}\rho_1 U_1{}^3 + U_1 B_1{}^2/4\pi + \rho_{i1} E_i U_1$$

where ρ, U and p are the densities, velocities, and pressures of the various species indicated by the subscripts N, i and e, for neutrals, ions, and electrons. B is the magnetic field; E_i is the ionization energy per unit mass, and C_p/R is the ratio of specific heat at constant pressure to the gas constant.

In addition to the above equations, the rates of change of the fluxes of mass, momentum, and energy of two of the three species must be described. For the neutrals these equations are

$$\underline{\text{Neutral Mass}} \qquad d/dx(\rho_N U_N) = - \overline{\sigma_i V_e}\ N_i N_N m_i$$

$$\underline{\text{Neutral Momentum}} \qquad d/dx(p_N + \rho_N U_N{}^2) = \overline{\sigma_{CT} V_R}\ N_i N_N m_i (V_i - U_N)$$

$$- \overline{\sigma_i V_e}\ N_i N_N m_i U_N$$

$$\underline{\text{Neutral Energy}} \qquad d/dx(\tfrac{1}{2}\rho_N U_N{}^3 + \frac{C_p}{R} p_N U_N) = \overline{\sigma_{CT} V_R}\ N_i N_N (kT_i +$$

$$+ \tfrac{1}{2} m_i U_i{}^2 - kT_N - \tfrac{1}{2} m_i U_N{}^2) - \overline{\sigma_i V_e}\ N_i N_N (\tfrac{1}{2} m_i U_N{}^2 + kT_N)$$

$$+ \overline{\sigma_{Ne} V_e}\ \delta_{Ne} N_i N_N (kT_e - kT_N - \tfrac{1}{2} m_i (U_N - U_i) U_i)$$

The electron density and flow velocity are given by the charge neutrality condition ($N_e = N_i$) and the boundary condition of no current perpendicular to the plane of the shock. And finally, the electron energy equation is

<u>Electron Energy</u> $$d/dx(N_e kT_e U_i) + N_e kT_e \frac{dU_i}{dx} = \overline{\sigma_{Ne} V_e}\, \delta_{Ne}$$
$$N_i N_N \left[kT_N + \tfrac{1}{2} M(U_N - U_i)U_N - kT_e\right] + \overline{\sigma_C V_e}\, \frac{m}{M_i} N_i^2$$
$$(kT_i - kT_e) - N_i N_N \overline{\sigma_i V_e}\, E_{ioniz}$$

where N_N, N_i, N_e and T_N, T_i, T_e refer to the number densities and temperatures of neutrals, ions, and electrons. The $\overline{\sigma V}$ are cross sections averaged with the appropriate velocity distributions where the subscripts i, CT, Ne, C refer to cross sections for ionization, charge exchange, neutral electron energy transfer, and Coulomb collisions, respectively. δ_{Ne} is the fractional energy transfer from neutrals to electrons per collision and m_e, m_i refer to the electron and ion or neutral mass. We have neglected joule heating of electrons, heat conduction by electrons in the flow direction, and assumed that the ions are strongly tied to the magnetic field lines, $(U_i/U_1 = B_1/B)$. Experimental cross sections were used where possible. If these were not available, theoretical estimates were used.[6,7,8]

This system of equations was solved by machine integration after starting values were calculated by linearization around the free stream conditions ahead of the shock. The calculations were done for hydrogen and since the dissociation mechanisms at these energies are not clearly understood, the calculations were carried out for both molecular and atomic species.

<u>Results, Low Alfven Mach Number, Atomic Cross Sections</u>

For this case the electron heating rate by elastic collisions with the ions was taken from Ref. 9 and for atoms, cross sections were taken from Ref. 6, assuming a fractional energy per collision of m_e/m_A. This electron heating rate allows little ionization within the shock and the shock structure is determined by the charge-exchange mechanism. Most of the ionization occurs in a relaxation region behind the shock. Typical magnetic field and ionization profiles

are shown in Fig. 1, for an initial degree of ionization of 0.1, Alfven Mach number of 2.0, a shock speed of 4×10^7 cm/sec. The shock thickness based on the magnetic field rise varies inversely as the initial degree of ionization. A thickness based on the light intensity rise (due to Bremsstrahlung) is, of course, the thickness of the ionization relaxation zone and therefore, is independent of the initial degree of ionization. The thickness based on the light intensity agrees to within a factor of two with previously published measurements[3] (Fig. 2). The thickness based on the magnetic field rise can be made to agree with the measured results[3] for an initial degree of ionization of 0.1.

This explanation is deficient in several respects. (1) In the MAST experiments, the initial degree of ionization is not carefully controlled and yet the magnetic thickness is quite reproducible. (2) The gas is not dissociated ahead of the shock and ordinary dissociation mechanisms do not appear to be fast enough to cause appreciable dissociation within the shock. (3) The predicted separation between the magnetic field rise and the ionization rise has not been observed. Recently, simultaneous measurements of magnetic field, visible light and soft x-ray emission (see Section 3) have been made. Preliminary results indicate that the magnetic field rise occurs very near or only slightly (1 cm) ahead of the x-radiation and visible light.

Results, Low Alfven Mach Number, Molecular Cross Sections

In the molecular case, if the heat transfer to electrons is assumed, as in the atomic case, to be due to elastic collisions with molecules and ions, we again find that ionization occurs behind the magnetic field change. However, since the charge exchange cross section is smaller for molecules, the calculated magnetic thickness is larger than the observed one at all initial degrees of ionization. The thickness of the ionization rise

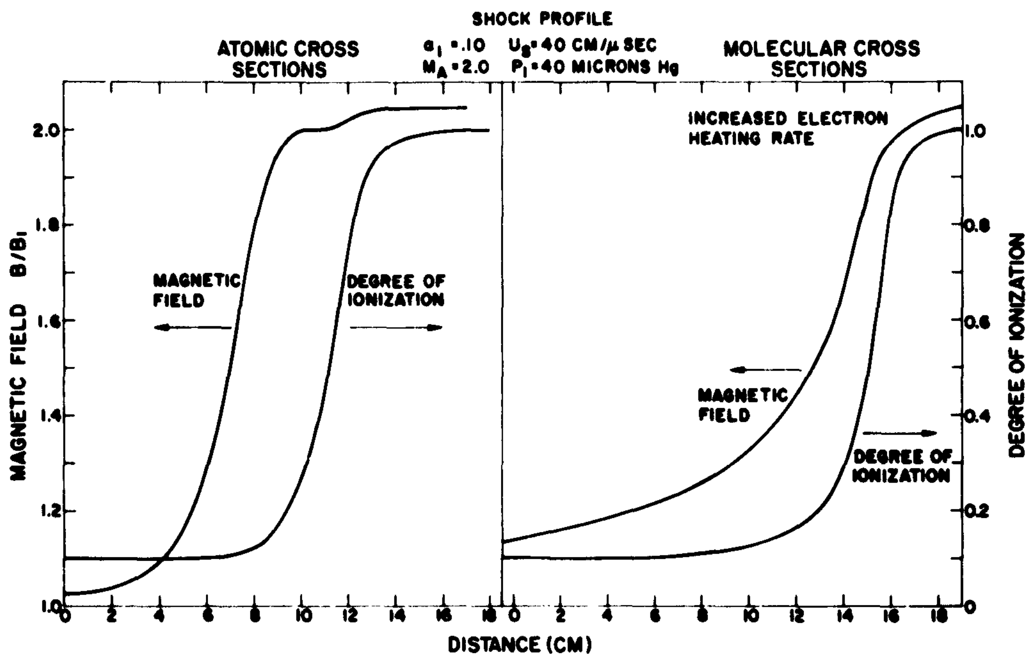

Fig. 1 Magnetic field and ionization profiles are shown for $M_A = 2$ shocks with both atomic and molecular cross sections used in the computations. For the molecular case, the electron heating rate is augmented as discussed in the text.

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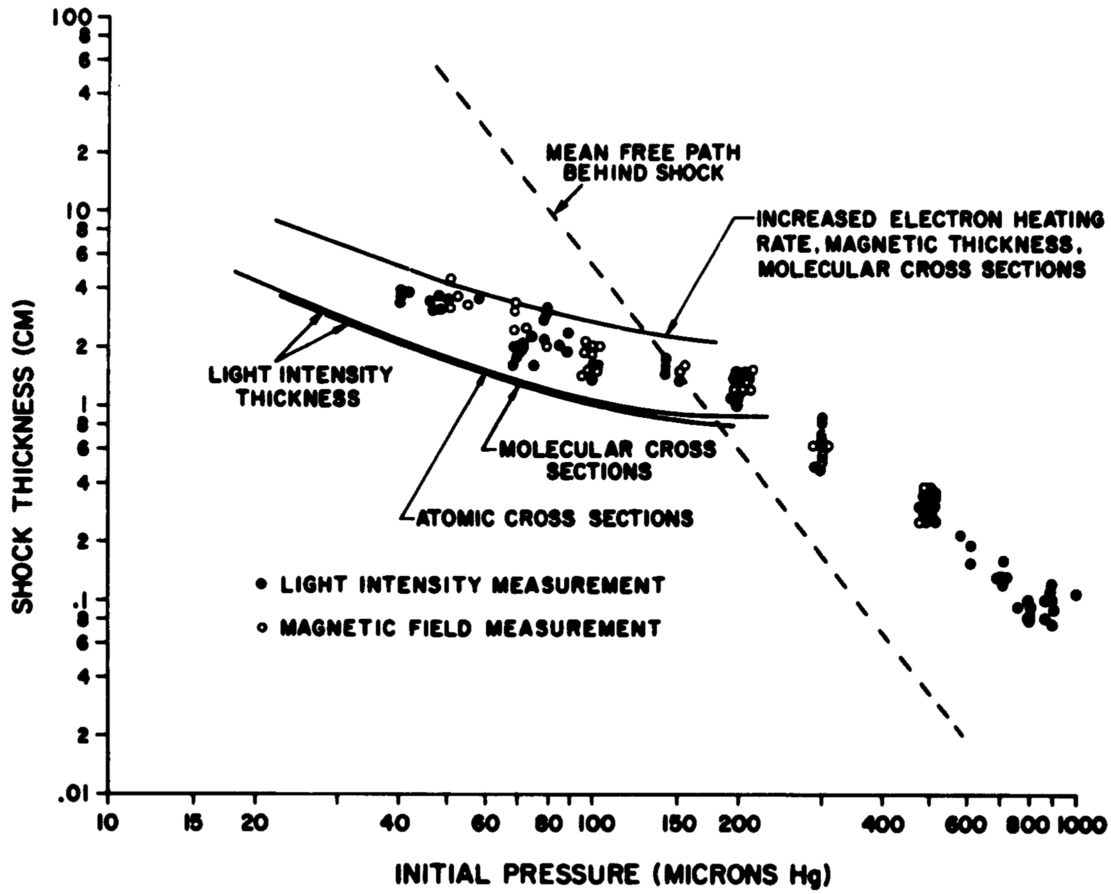

Fig. 2 Theoretical shock thicknesses are compared with experiment for both atomic and molecular cross sections. For the atomic case, only the light intensity thickness is shown as the magnetic thickness depends on the initial degree of ionization. The curves and points shown are for $M_A = 2$ for which the shock velocity scales with pressure as $U_1 = 253/(P_1)^{\frac{1}{2}}$. ($P_1$ in microns; U_1 in cm/μsec.)

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again agrees to within a factor of two with experiment.

Several additional calculations were done for the molecular cross section case in which the electron heating rate was increased by a factor ranging from 10 to 500 above that due to elastic collisions. In all of these cases, a shock profile was obtained in which the major portion is dominated by the ionization mechanism, (Fig. 1) and both the magnetic and light intensity shock thicknesses are within a factor of two of each other and bracket the experimental data[1, 3](Fig. 2). In addition, both thicknesses are relatively independent of the initial degree of ionization and of the amount of increased electron heating, if the increase is greater than a factor of 10.

An increased electron heating rate cannot be attributed to the transfer of energy from vibrational or rotational degrees of freedom of the molecule since the electron temperature in the region of interest is greater than 10 ev, and molecules with an internal energy corresponding to this temperature would dissociate rapidly. Thus, at present the increased electron heating is artificial, but may be due to several effects which have not been included in the present calculations. Among these is heat transfer forward along field lines by the electrons, since in the experiment, there was a small component of axial bias field present. Further work to clarify these points is in progress.

High Alfven Mach Number Theory

For Mach number greater than two, where the effects of viscosity must be included, the calculations have been carried out with an additional set of assumptions. For the low Alfven Mach number atomic cross section cases, the ionization occurred behind the shock, for this reason, we have assumed the degree of ionization constant in the high Mach number cases;

further, we have assumed it to be small. The charge-exchange cross section was assumed to be independent of energy and the viscosity was approximated by the simple kinetic formula $\mu = 3/4\rho\lambda\bar{c}$ where λ is the mean free path for a neutral to charge-exchange with an ion. The Prandtl number $(\mu C_p/k)$, was assumed to be .75. The results, shown in Fig. 3, indicate a smooth transition between a shock structure dominated by the previously discussed charge-exchange process near $M_A = 2$, to a structure dominated by charge-exchange viscosity for high Mach numbers.

3. Conditions Behind Shock

Previous measurements[3] justify use of the conservation conditions to determine conditions behind the shock. The conservation conditions, however, do not determine the distribution of energy between electrons and ions. In order to try to determine this, the soft x-ray emission was measured.

Soft X-Ray Detector

The soft x-radiation emission from the plasma has been measured at photon energies between 200 and 270 ev. This was done with calibrated detectors which employ thin ($\approx 10^4$A) carbon foils as soft x-ray filters. (Fig.4) The detector consists of a thin carbon foil which is opaque to ultraviolet and visible radiation, a plastic scintillator to convert the x-radiation to visible radiation and a photomultiplier to measure the visible radiation emitted by the scintillator. The carbon foils were made with a pyrolysis process. This apparatus consists of a platinum strip 2.5 cm wide, 10 cm long, and 2×10^{-3} cm thick in a chamber filled with a (3:1) mixture of argon and methyl iodide. The total gas pressure was 20 cm Hg. The platinum strip is heated by a 40 ampere current for 5 minutes, and during this time, carbon is deposited on the strip. After 5 minutes, the current is turned off which quickly cools

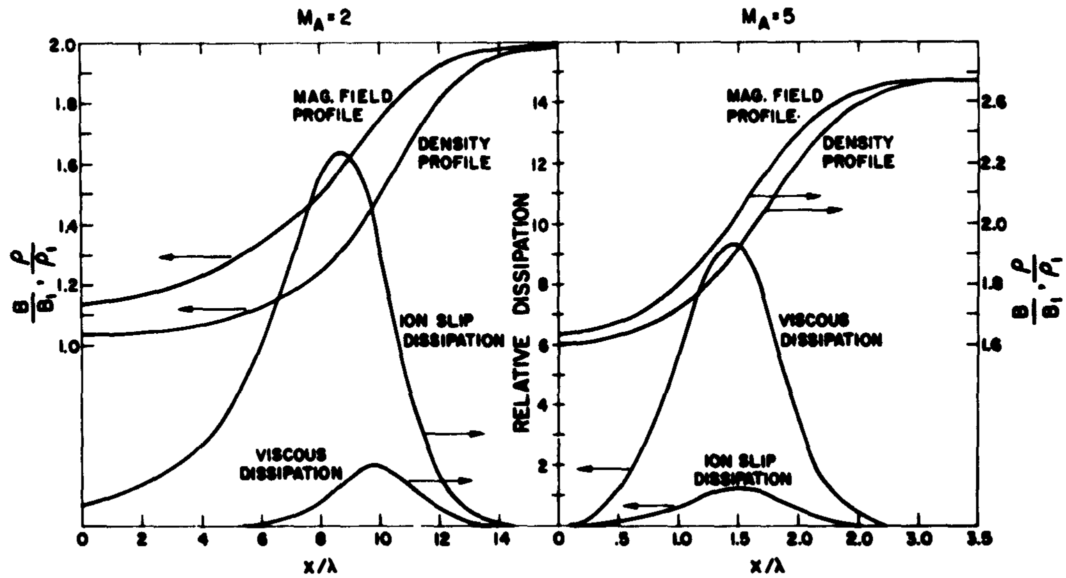

Fig. 3 The magnetic field and density shock profiles are shown for two Mach numbers; one where the dissipation is largely ion slip ($J \cdot E$) and the other where the dissipation is largely $\mu(du/dx)^2$. The dissipation rates are suitably nondimensionalized.

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PLASMA X-RAY DETECTOR

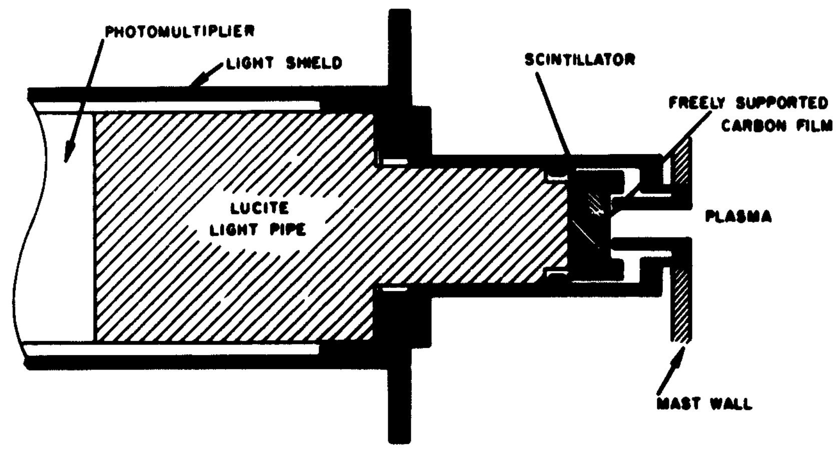

Fig. 4 Soft x-ray detector with a response time less than 10^{-8} seconds.

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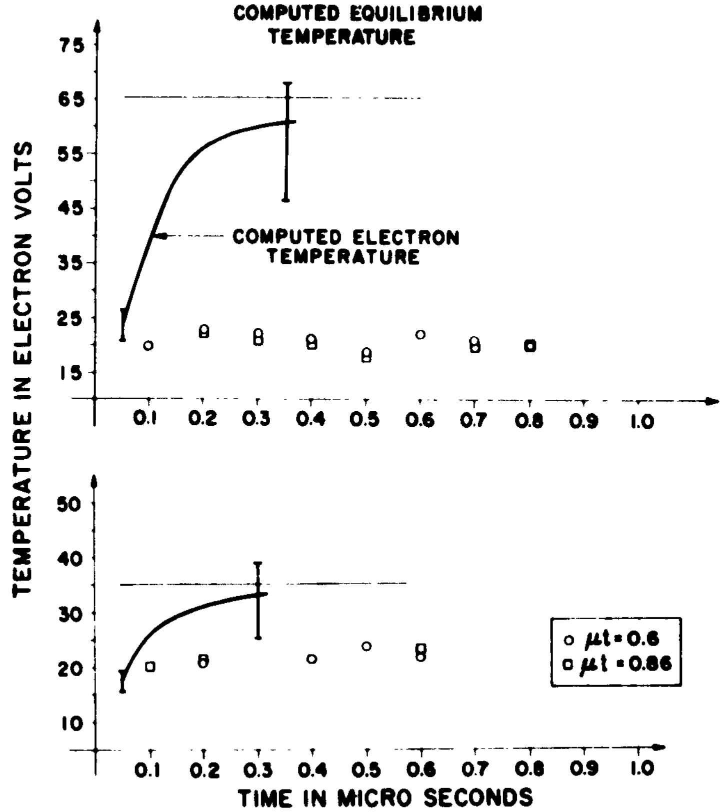
the strip and facilitates the removal of the carbon foil from the platinum strip. Any small holes in the foil are covered with a solution of alcohol and carbon black. The detectors were calibrated by using an x-ray source which consisted of a tungsten filament and a carbon target. When the voltage between the filament and target was held slightly above 300 volts, the major portion of the soft x-ray emission from the target is line radiation near 44A. The radiation as a function of filament current from this x-ray tube was measured with a Geiger Mueller tube, and this source was used to obtain a direct calibration of the soft x-ray detector at 44A. This x-ray source was also used to measure the carbon foil thickness, by measuring the attenuation of this beam due to the introduction of the foils in the beam. The foil thickness together with the overall calibration of the soft x-ray detector at 44A was used to obtain a response of these detectors as a function of wavelength between 43A and 100A.

The radiation intensity from an equilibrium plasma decreases exponentially with an increase in frequency in this spectral range. Hence, the wavelength at which maximum photocurrent is produced is both a function of the plasma electron temperature and the carbon foil thickness. Therefore, two detectors with different foil thickness will have their maximum sensitivities at different wavelengths. Two detectors with foil thicknesses such that the product, μt, (the thickness times the absorption coefficient of carbon at 43A) was 0.60 and 0.87, were used to obtain the data shown on Fig. 5.

An oscillogram of the voltage output of a soft x-ray detector is shown in Fig. 5. This oscillogram was obtained by terminating the output of the detector with an integrating circuit with an integrating time equal to 5×10^{-8} seconds. This integration was necessary because the duration of the output

SOFT X-RAY MEASUREMENTS



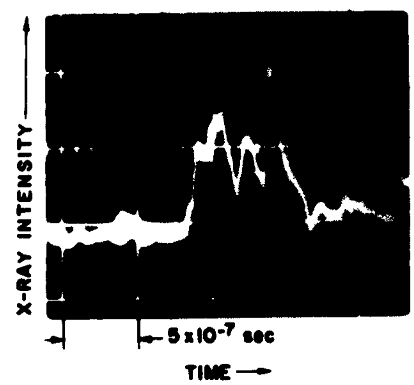


Fig. 5 Measured electron temperatures behind two shocks from two x-ray detectors. Squares for foils where $\mu t = 0.6$; circles $\mu t = 0.86$; data is plotted versus laboratory time after shock arrival. Top data was obtained from faster shock when equilibrium temperature equaled 65 ev; the bottom run for 35 ev. The error bars on the computed electron temperature curves represent the range in electron temperature profiles due to the uncertainty in measuring shock speed (10%). The oscillogram shows the integrated output of a soft x-ray detector. The minimum measurable x-ray flux corresponds to a 14 ev electron temperature.

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signal from the photomultiplier in the x-ray detector due to a single photoelectron was 5×10^{-9} sec. The x-ray flux could be measured by counting the number of these pulses on an oscillogram, except when the intensity of x-rays from the plasma was sufficiently high to make an accurate count on an oscillogram difficult. In this case, the integrated signal could be used to give an accurate time averaged value. The integration time of 5×10^{-8} seconds was chosen to be of the same order as the time required for the electron distribution to Maxwellize out to 270 volts for the densities of interest. This time, for electron densities equal to $10^{16}/\mathrm{cm}^3$, is approximately 10^{-7} sec.

Soft X-Ray Results

The soft x-ray measurements can be used to obtain an estimate of the electron temperature. The intensity of the free-bound and free-free radiation from the plasma was computed assuming a Maxwell distribution for the electrons. The electron density was obtained by measuring the intensity of the continuum radiation in the visible. The electron density and calculated soft x-ray emission were used to convert the measured soft x-radiation results to electron temperature measurements.

Some of the results of the soft x-ray measurements which yield the electron temperature are shown in Figs. 5 and 6. The shock velocity was measured over a distance of 45 cm upstream of the point where the soft x-ray measurements were made. This information was used to compute the equilibrium conditions behind the shock as a function of laboratory time at the x-ray port. The calculated equilibrium temperatures based on these measurements are shown on Fig. 5. The computed electron temperature profiles behind the shock shown are calculated from initial values given by the charge exchange ionization shock theory and proceed to equilibrium by

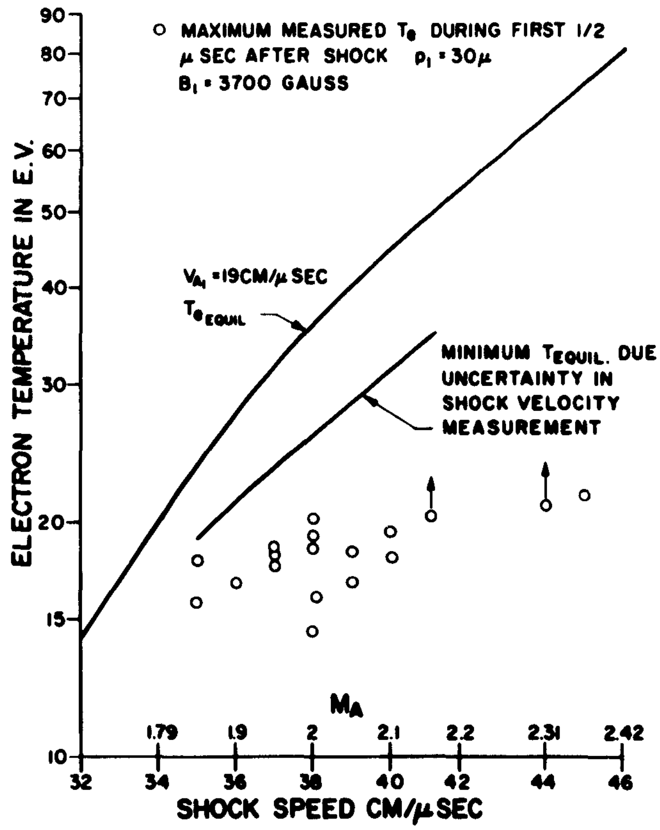

Fig. 6 Summary of measured electron temperatures versus shock speed for a given initial condition. The equilibrium temperature is based on the Rankine-Hugoniot shock conditions.

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proton-electron collisions. Both the equilibrium temperature and electron temperature profiles are sensitive functions of the shock velocity. The error bars on the electron temperature profiles shown in Fig. 5 indicate the possible error in estimating the electron temperature due to the 10% uncertainty in the measured shock velocities. The electron temperatures shown in Fig. 5 are in some agreement with the theoretical value immediately behind the shock, but are substantially below the calculated values during the test time. The soft x-ray signals also give a measure of the test time or the length of the homogeneous gas sample which is in agreement with the previous results.[1]

The electron temperature corresponding to the maximum x-ray signal during the test time as a function of shock speed for a fixed set of initial conditions is shown in Fig. 6. In addition, the computed equilibrium temperature based on the shock speed is shown. The minimum value of the equilibrium temperature due to the uncertainty in shock speed measurement (10%) is also shown. It can be seen by inspecting Fig. 6 that the measured electron temperatures are substantially below the calculated equilibrium temperatures for the whole range of shock velocities achieved in the recent MAST experiments.

The apparent discrepancy between the electron temperature inferred from the x-radiation and the calculated electron temperature has several possible explanations. Two possibilities are discussed below:

First, the electrons might lose their energy to the MAST walls. The time resolved heat transfer to the side wall was measured by Camac.[3] These results showed that less than 10% of the plasma thermal energy was lost to the side walls during the test time. The heat transfer was measured with a fast infrared bolometer, which used an infrared sensitive cell to

measure the back surface temperature of a carbon foil placed on the wall of the MAST. Recently, some measurements of the heat flux to one of these gauges was made when the gauge was mounted at a 15° angle to the wall with the leading edge of the gauge in contact with the wall. With the gauge at an angle, a much larger heat flux was measured, a flux which corresponds to the computed flow enthalpy in the plasma. These results show that the plasma energy created by the shock is not lost to the walls.

Second, for equilibrium temperatures between 40 and 70 ev, the electron distribution must be Maxwellian to energies between 4 and 5 times the average equilibrium energy to give equilibrium x-radiation between 40A and 100A. One would expect this equilibrium to be established in a short time (10^{-7}sec). However, if a mechanism exists which depletes the tail of the distribution, one may make large errors in estimating the average electron energy by measuring radiation at these wavelengths.

At the present time, we do not understand the disagreement between the x-ray measurement of the electron temperature and the expected values based on the measured shock speeds and relaxation time between ions and electrons.

Concluding Remarks

The results of the theoretical analysis show that ionization and charge-exchange processes can dominate the structure of a MHD shock propagating into partially ionized hydrogen. The soft x-ray emission from the plasma created by these shocks in a MAST has been measured. The measurements indicate that the electron temperature immediately behind the shock is approximately equal to 20 ev (which is in rough agreement with the theory). Further behind the shock, the measured x-ray flux is much

Acknowledgement

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MAGNETOHYDRODYNAMIC SHOCK STRUCTURE IN A PARTIALLY IONIZED GAS, by E. T. Gerry, R. M. Patrick and H. E. Petschek. June 1963. 19 p. incl. illus. (Avco-Everett Research Report 153)
(Contracts AF 49(638)-1129 and Nonr-2524(00).

Unclassified report

A study has been made of strong MHD shock waves in partially ionized hydrogen. Dissipation due to slip between the ions and neutrals with the effects of viscosity and heat conductivity have been included. Charge exchange processes control viscosity and ion slip. For Alfven Mach numbers below 2.5, the dominant mechanism is ion slip; for larger Mach numbers, the viscosity is important. The measured light intensity rise time and the electron temperature immediately behind the shock agree with theory. Behind the shock, measured electron temperatures are low. Electron temperatures are obtained by measuring the plasma soft x-radiation using thin carbon foils as filters.

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2. Shock tubes, magnetic annular.
3. Shock waves, magnetohydrodynamic.
4. Plasma physics.

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"Magnetohydrodynamic Shock Structure in a Partially Ionized Gas"

by

E. T. Gerry, R. M. Patrick and H. E. Petschek

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Also, page 19 is incomplete, please replace it with the attached new page 19.

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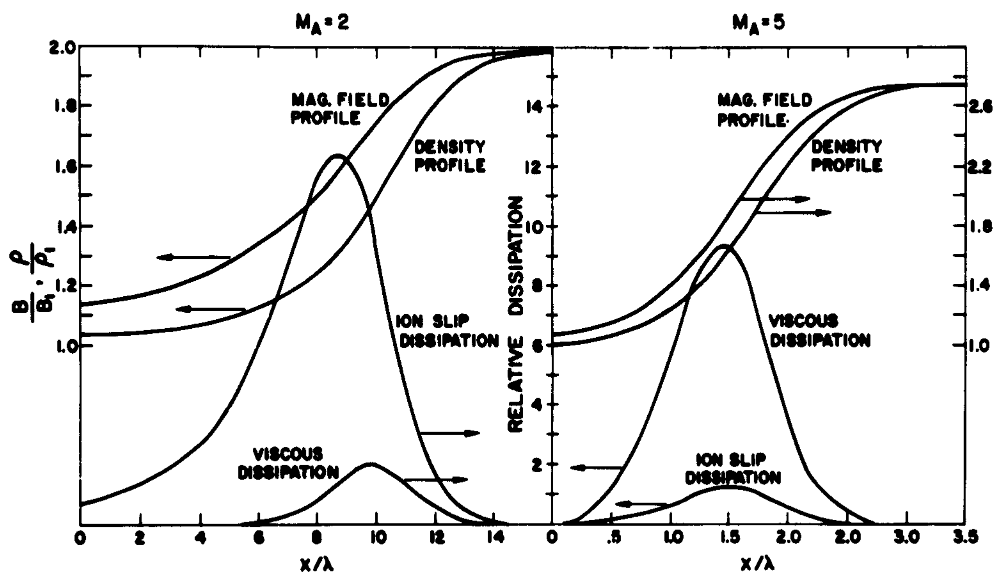

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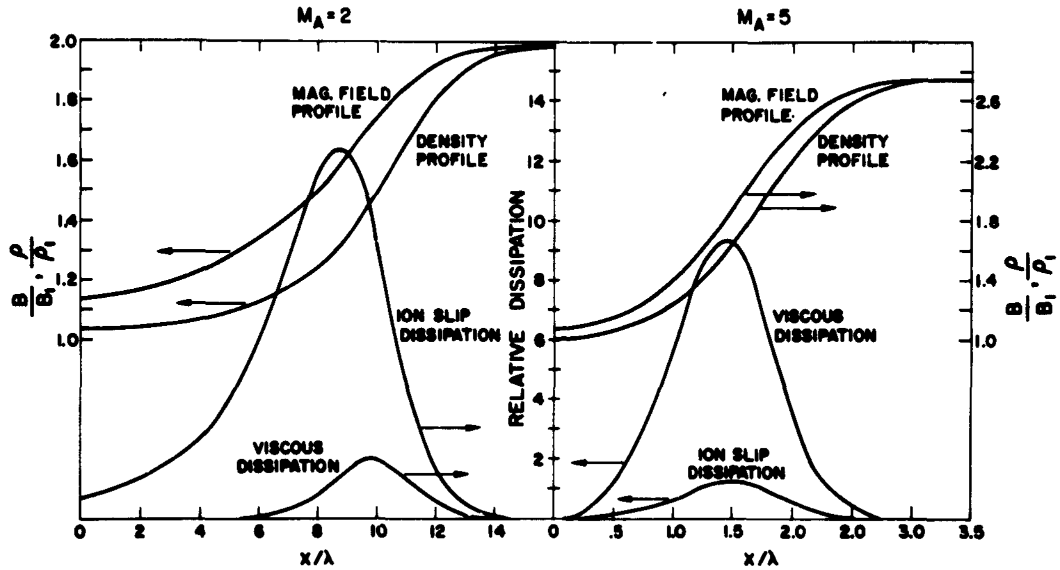

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4. Kantrowitz, A.R., Proceedings of the Fiftieth Anniversary Solvay Conference, Brussels, Belgium, Nov. 5-10, 1962. Avco-Everett Research Laboratory Research Report 141.
5. Camac, M., et al, Nuclear Fusion, 1962 Supplement, Part 2, p. 423.
6. Brown, S.C., Basic Data of Plasma Physics. John Wiley & Sons, New York, 1959.
7. Gurnee, E.F. and Magee, J.L., J. Chem. Phys., 26:1237 (1957).
8. Simons, J.H., et al, J. Chem. Phys., 11:312 (1943).
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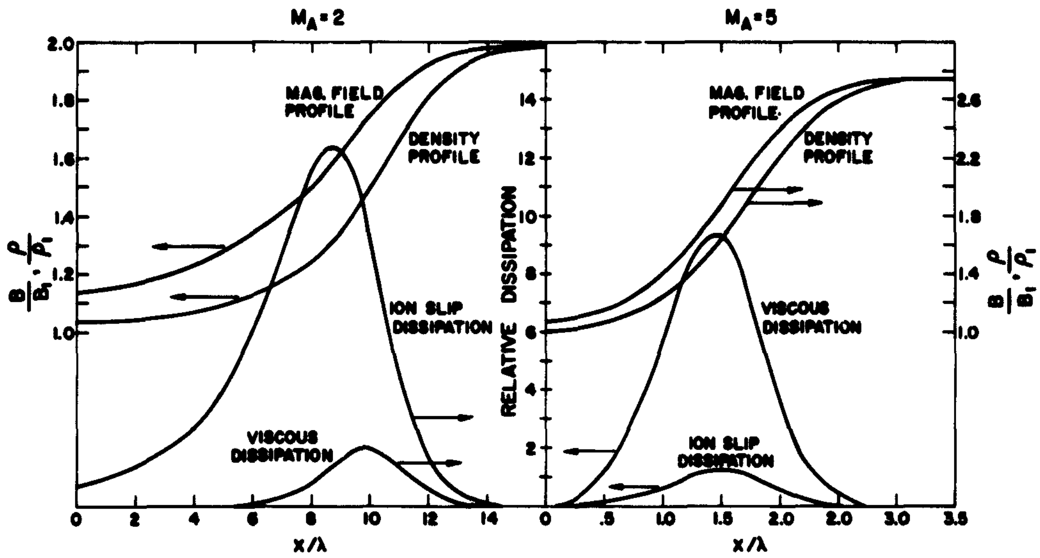

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